CHANGES OF GLACIERS IN GLACIER BAY, ALASKA, USING GROUND AND SATELLITE MEASUREMENTS

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Abstract: The deglaciation of Glacier Bay, Alaska is studied using historical maps, field measurements, and satellite imagery. In general, both tidewater and non-tidewater glaciers in the area have receded during the last century, but the rates of recession are quite variable, especially in the case of the tidewater glaciers. Available average air temperature data from nearby meteorological stations show a general warming trend, especially over the last 20 years. Such a warming trend may help to explain recession of the non-tidewater glaciers of the area. Comparison of September Landsat multispectral scanner imagery from 1973 and 1986 shows that the amount of vegetation increased significantly and rapidly as glaciers receded. The vegetation within a Landsat subscene covering Muir Inlet increased about 86% during the 13-year period. The once-impressive Muir Glacier, a tidewater glacier, has receded dramatically since the late 1800s. Satellite measurements show that the terminus retreated >7.3 km between 1973 and 1992. Work accomplished by researchers earlier in this century has been extended using satellite techniques, allowing us to study glacier changes quantitatively in the entire Glacier Bay region over the past two centuries.

INTRODUCTION

Formerly the Muir presented a perpendicular front at least 200 feet in height, from which huge bergs were detached at frequent intervals. The sight and sound of one of these vast masses falling from the cliff, or suddenly appearing from the submarine ice-foot, was something which once witnessed was not to be forgotten. It was grand and impressive beyond description. Unfortunately the recent changes in the Muir have not increased its impressiveness from a scenic standpoint. Instead of the imposing cliff of ice, the front is sloping, and seems to be far less active than formerly. The eastern arm discharges but little, and appears to be nearly dead. The front of the western arm is in [the] shape of an elongated basin, and, as above stated, slopes gently.

—Freemont Morse, 1905 (from Bohn, 1967)

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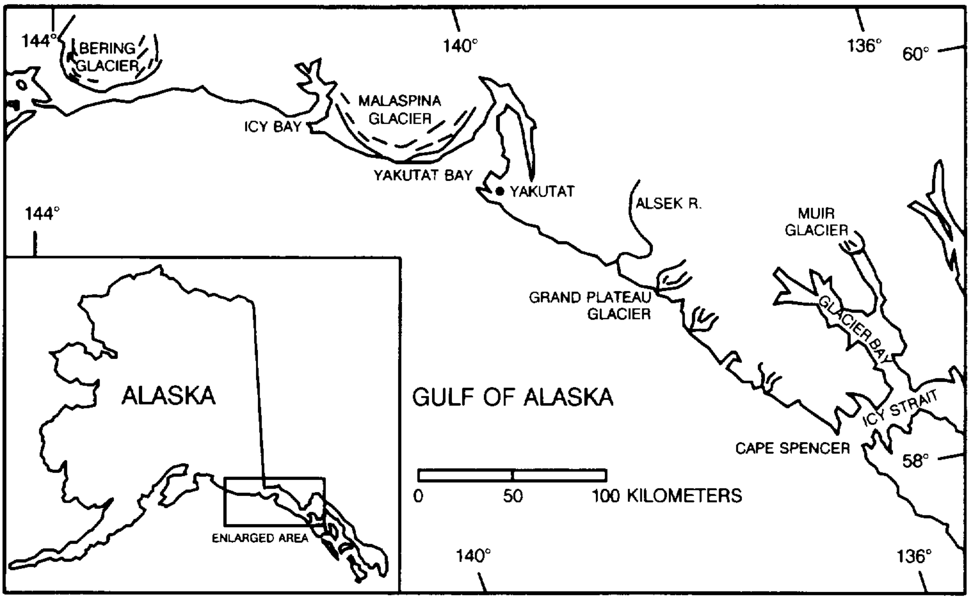
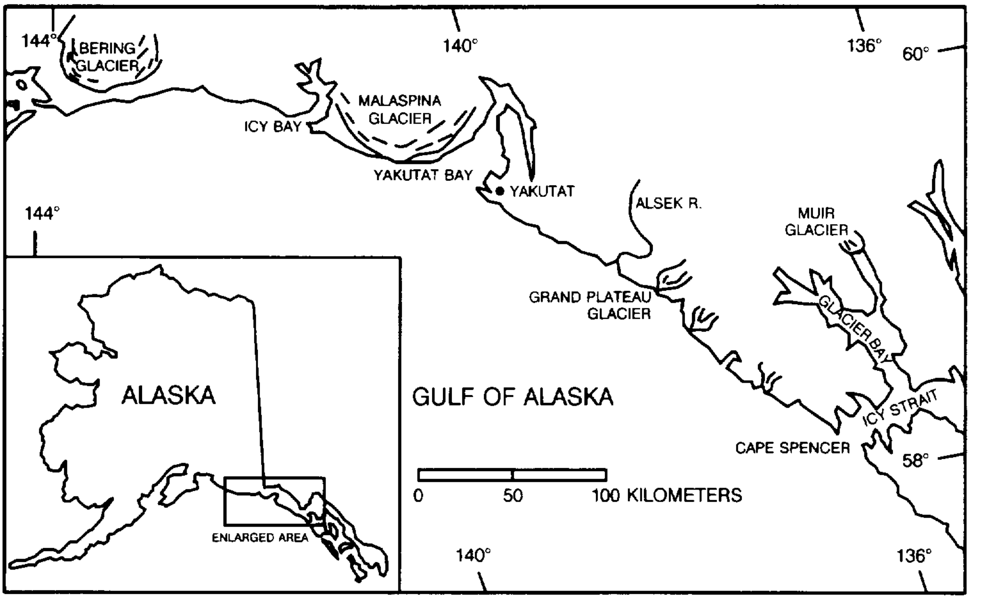


Fig. 1. Location of Glacier Bay in Alaska (after Molnia, 1989).

Glacier Bay (Fig. 1) contains both tidewater and non-tidewater glaciers, many of which have been in a state of rapid retreat since the late 1700s (Field, 1932, 1947). From the mid-19th to the mid-20th centuries, the area covered by glaciers draining to Muir Inlet was reduced about 35%, or about 452 km^2; the area of sea water increased by about 122 km^2 (Field, 1947). About 200 years ago there was a massive ice field that extended into Icy Strait and filled the bay. By 1794 the ice had retreated and opened a small bay, and by 1879 the retreat had exceeded 60 km (Molnia, 1982). The impressive Muir Glacier of the 1890s, referred to in the first paragraph, with its many tributary ice streams, has shrunk dramatically.

Glaciers of the Northern Hemisphere receded to their smallest extent since the last Ice Age during the relatively warm Hypsithermal interval, which lasted several thousand years, from about 7100 to 2200 B.C. (Goldthwait, 1966). At its peak around 6000 years ago, global mean temperatures were estimated to be 1° C higher than at present (Goldthwait, 1966; Denton and Porter, 1970). Following the Hypsithermal, the climate cooled somewhat erratically until the Earth experienced the Little Ice Age. During the Little Ice Age, which lasted at most from about 1300 to 1880 A.D., the global mean temperature was 2° C or more lower than it is today (Goldthwait, 1966), and mountain glaciers of the world were significantly larger.

Mountain glaciers are especially good indicators of regional climate change (Oerlemans, 1986, 1994). Globally, mountain glaciers generally have been retreating since the end of the Little Ice Age. The volume of glaciers in the mountain regions of the temperate zones, of which about 88% are in the Northern Hemisphere, appears to have been reduced by between 10 and 20% in the last 125 years (Field, 1975).



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The Glacier Bay area is a fine example of rapid deglaciation, even though it is not clear how much recession is the result of climate amelioration and how much is the result of the tidewater glacier cycle and independent of short-term regional climate, as discussed later.

In this paper, we use geographic information system techniques to merge maps with satellite data to study glacier-terminus changes and vegetation regrowth during deglaciation in and near Glacier Bay, Alaska.

BACKGROUND

Very few glaciers are monitored on a worldwide basis, and it therefore can be difficult to determine trends in glacier mass balance. Of the approximately 7500 glaciers in the United States, as of 1980, only 101 were monitored regularly for changes in glacier-terminus position (Wood, 1988). Glaciers monitored for variations in glacier-terminus position probably account for less than 1% of the total number and area of glaciers worldwide. And the number of glaciers monitored for mass balance is only about one-tenth of the total number monitored (Wood, 1988).

The most common method for determining changes in the mass balance of a glacier is mapping historic ice-front position (van der Veen, 1991). However, changes in the length of a glacier are not necessarily proportional to changes in ice volume. It is possible for a glacier to increase in volume while its front is retreating (Meier, 1984). Generally, however, glaciers with a negative mass balance will retreat, given time, and glaciers with a positive mass balance will advance. Thus when glaciers are studied over a period of many years, sustained terminus-position change is a meaningful indicator of mass balance, whether positive or negative.

A tidewater glacier is a glacier that ends in the sea. The advance phase for a typical tidewater glacier is about 1000 years, whereas the retreat phase may be only about a century. Post (1975) and Meier and Post (1987) showed that stable tidewater glaciers terminate in shallow water, generally at the head of a fjord or on a moraine shoal. Tidewater glaciers that are in a state of rapid retreat terminate in deeper water once they retreat from the moraine shoal on which they were resting.

It is difficult and expensive to obtain mass balance or even ice-front position measurements in many glacierized areas because of bad weather and difficult access. With satellite data it is possible to study ice-front positions of numerous glaciers over large regions at a relatively low cost compared to the cost of field measurements. When satellite data are combined with in-situ measurements and aerial photographs, glacier-terminus position changes can be reconstructed over the previous century or even longer.

While satellite data allow measurements of ice-front position and other characteristics of glaciers, the measurements suffer from lower precision than is obtainable by field measurements. The precision of the satellite measurements is limited to the resolution of the satellite sensor. On many glaciers, ice-front position, snowlines, and equilibrium lines may be measured using satellite data (Knight et al., 1987; Sturm et al., 1991; Williams et al., 1991; Hall et al., 1992; Lingle et al., 1993).

History of Observations in Glacier Bay, Alaska

Written records of the ice in Glacier Bay began with observations by George Vancouver in 1794. Scientific expeditions to Glacier Bay began in the late 1870s. John Muir, naturalist and explorer, visited Glacier Bay in the 1880s and 1890s and studied the Muir Glacier. After Muir's visits, the Muir Glacier again was studied by G.W. Lamplugh in 1884 and by G. Frederick Wright in 1886 (Tarr and Martin, 1914). All the ice tongues were studied and mapped by H.F. Reid, H.P. Cushing, and Wright in the 1890s.

From 1794 to about 1860, a single ice front in Glacier Bay receded 30–40 km. After 1860, two ice fronts existed and they receded up the Tarr and Muir inlets at very different speeds. In Tarr Inlet, the ice front receded by about 35 km (about 1.1 km/yr) between 1860 and 1892, while during the same time span it went back only 7 km (0.2 km/yr) in Muir Inlet. From 1794 to 1892, there was an 80-km (0.8 km/yr) recession in the western side of Glacier Bay and a 40-km (0.4 km/yr) recession on its eastern side. Recession continued another 15–20 km in the western bay until 1920–1930, when the Johns Hopkins and Grand Pacific Glaciers began to advance. For a discussion of the retreat of the Grand Pacific Glacier, see Clague and Evans (1993).

Muir Glacier. The Muir Glacier of the 1890s, with its many tributary ice streams, was dismembered by recession (Field, 1947). Figure 2 shows changes in the Muir Glacier from 1941–1982 (Field, unpublished). The positions of the terminus and station sites were derived from a triangulation survey based on USGS 1:63,360 topographic maps.

From 1926 to 1982, Muir Glacier retreated 30 km, and the ice surface decreased by 670 m at the position of its 1982 terminus (Krimmel and Meier, 1989). The change from 1982 to 1993 has not been surveyed, but the photographic record indicates some shrinkage in the lower part of the glacier. There have been seasonal and annual changes in the shape of the terminus, owing to the deposition of outwash in front of the terminus, which reduced the rate of calving to practically nil in 1993. Nevertheless, the glacier appears to be shrinking slowly in terms of its activity and the elevation of its surface in the lower few kilometers.

Although the Muir Glacier generally has been retreating since at least the late 1700s, there was some sporadic advance activity during that time. Further details concerning the changes of the Muir Glacier were presented by Wright (1887) and Field (1947, 1948, and 1975).

Other Glaciers. Most of the valley glaciers of Glacier Bay either currently terminate in water, or did so previously. While some glaciers appear to have a stable ice-front position over about the last 30 years, most others are retreating and some are advancing. This applies to valley glaciers and only a few prominent hanging glaciers, as we have comparatively few data on many small cirque and hanging glaciers. The nearby Brady Glacier has been relatively stable since it reached a maximum in the last quarter of the 19th century, although it began a slow advance around 1961 (Derksen, 1976). In summary, although there has been mixed activity on many of the glaciers in Glacier Bay, the overall trend is toward retreat of both tidewater and non-tidewater glaciers.

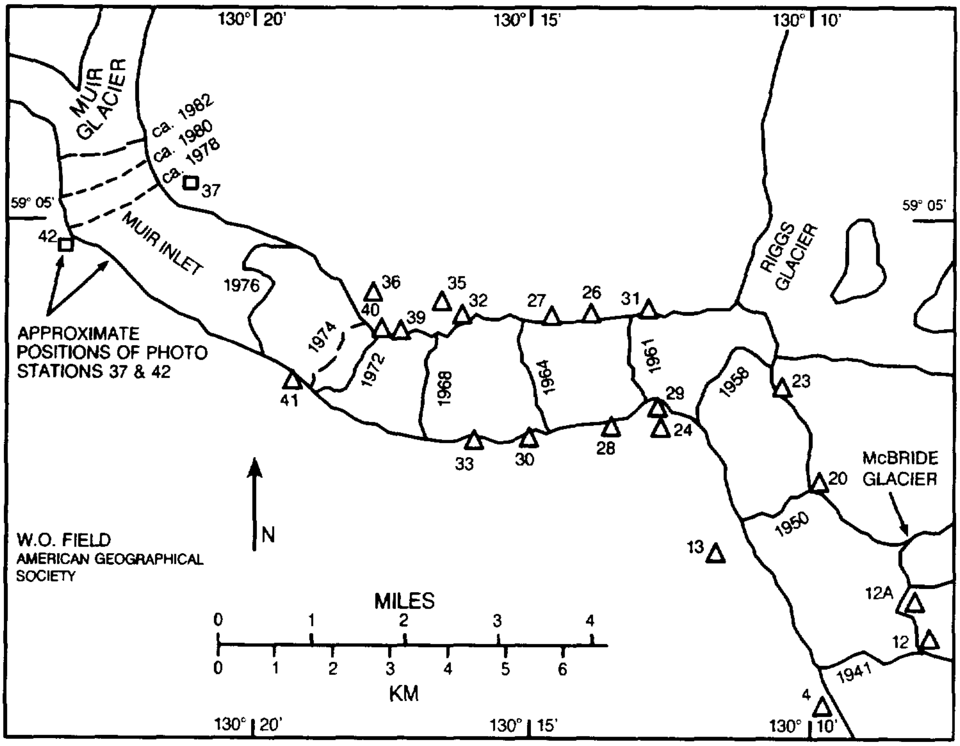

Fig. 2. Recession of Muir Glacier, 1941–1980 and extended to show the approximate changes up to 1982. American Geographical Society survey and photo stations are indicated by triangles and their numbered designations. The positions of the Muir terminus are from AGS surveys in 1941, 1950, 1958, 1961, 1964, 1968, 1974, and 1976. The 1972 position is taken from USGS 1:63,360 series topographic series, Skagway A-4, 1961, with limited revisions in 1972. The 1979 and 1980 positions are from Austin Post (personal communication) and the 1982 position is an estimate from terrestrial and aerial observations. Sketch map drawn by W.O. Field and redrawn for publication.

STUDY OF GLACIERS USING SATELLITE DATA

Landsat multispectral scanner (MSS) and thematic mapper (TM) data have been available since 1972 and 1982, respectively, and are valuable for studies of glacier dynamics (Meier, 1973; Krimmel and Meier, 1975; Williams, 1976; Hall et al., 1992). MSS (79-m picture element (pixel) resolution) and TM (29-m pixel resolution) data may be used to determine changes in the position of a glacier terminus by comparing sequential images. In addition, Landsat data are useful for measuring the position of the equilibrium line and for estimating mass balance change when calibrated with previous field measurements of glacier mass balance (Ostrem, 1975). The equilibrium line separates the area of a glacier that has a net gain of mass over the year (accumulation area) from that area having a net loss (ablation area) (Benson, 1962; Paterson, 1981). In this paper, we discuss only changes in glacier-

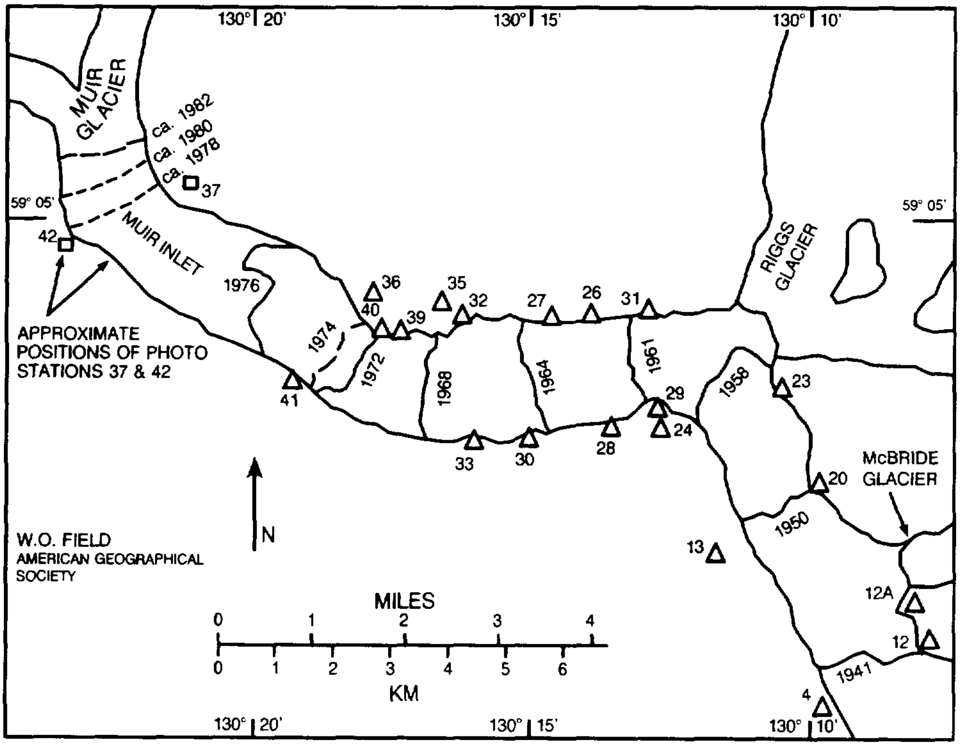

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Table 1. Landsat Data Used in This Study

Date	Landsat sensor	Scene identification number
12 September 1973	MSS	81416194805
20 September 1980	MSS	82206819365
06 September 1983	MSS	84041719421
06 September 1986	MSS	85091919333
16 October 1992	TM	4059019009229010

terminus position that, used in conjunction with other information, can provide information about changes in glacier mass balance if studied over a period of time.

Satellite-borne synthetic aperture radars (SAR) have provided an excellent source of remote sensing data for glaciers. They have the advantage of being able to acquire high-quality data through cloud cover and darkness; they also can obtain data from below the surface, whereas Landsat data represent the surface or very near-surface only. Two satellite-borne SARs currently are operational, one from the European Space Agency, since 1991, and the other from the Japanese Space Agency, since 1992. These data are proving to be useful for measurement of glacier-terminus position and other features that may relate to the glacier-facies boundaries (Lingle et al., 1993; Fahnestock et al., 1993; Benson, 1994). Both Landsat and SAR data may be used together to measure glacier-terminus position and the elevation of the equilibrium line.

Sources of Data

Landsat MSS and TM data acquired from 1973 to 1992 were used in this paper (Table 1). We used three bands of MSS data: bands 2 (0.5–0.6 μm), 3 (0.6–0.7 μm), and 4 (0.8–1.1 μm), and three bands of TM data: bands 2 (0.52–0.6 μm), 4 (0.76–0.9 μm), and 5 (1.55–1.75 μm). All Landsat data, discussed herein, are in digital form from the MSS sensors except the 1992 scene, which was acquired by the TM sensor. The 1992 image was acquired in September when the sun elevation was lower than at the time of acquisition of the August scenes; thus shadows cast by mountains were larger. The larger shadows precluded accurate measurement of most glacier termini in 1992. Figure 3 shows the 6 September 1986 Landsat MSS image of Glacier Bay and adjacent areas. Subscenes of this full scene are discussed in more detail later. The 1977 and 1978 Landsat data are in image form only, and were not digitized for this study. Owing to the expense of the TM data, the MSS data are used as the primary data source.

Maps are used to identify the positions of a glacier's terminus, prior to availability of Landsat data. A 1966 map (Fig. 4) presented by Bohn (1967) was digitized and registered to the Landsat data so that changes between 1966 (or earlier, in some cases) and 1986 could be measured.

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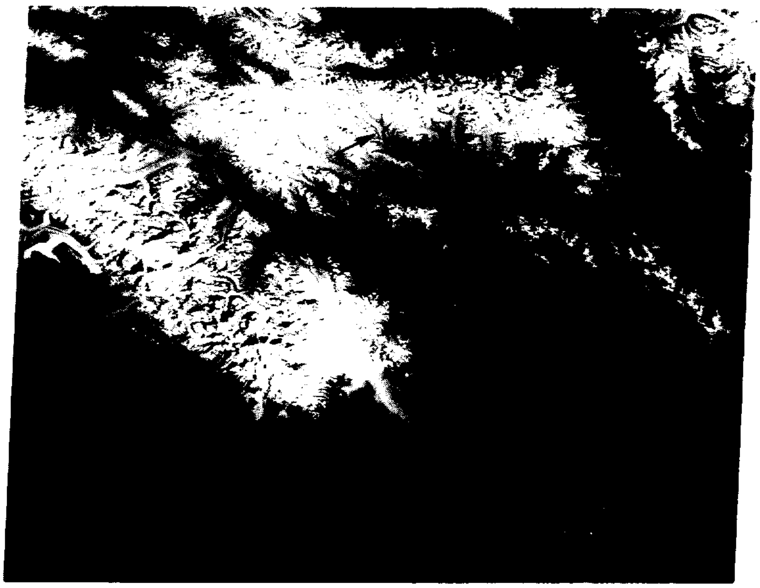


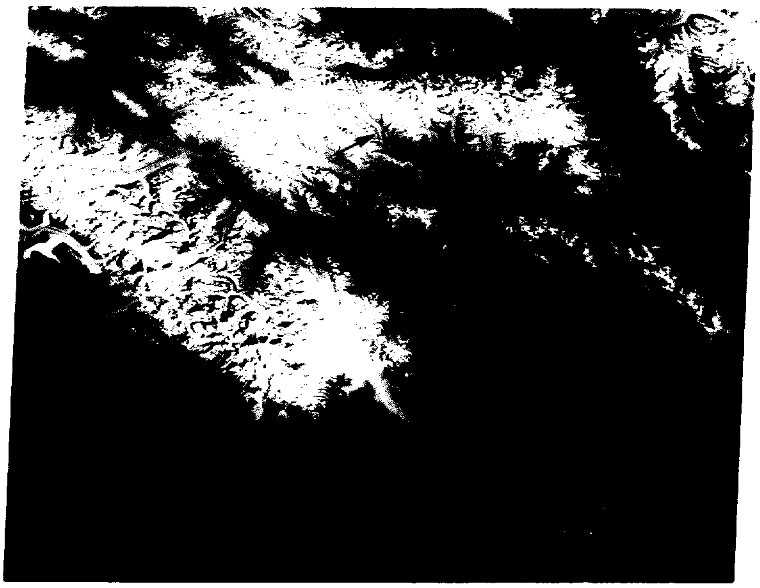
Fig. 3. Full Landsat MSS scene acquired 6 September 1986 (I.D. #85091919333) showing Glacier Bay in Alaska. Arrow points to the Muir Glacier. MSS bands 2, 3, and 4 were used to construct this false-color image. Red areas represent vegetated terrain.

Merging Maps and Satellite Data for the Study of Changes in Glacier Bay, Alaska

All Landsat data (Table 1) were registered to the 1986 MSS scene, which was used as the "master" scene. Thus, even though the TM data have an inherent pixel resolution of about 29 m, the 1992 TM data were resampled to be consistent with the approximately 79-m MSS resolution of the MSS. In order to perform an accurate measurement of changes in the position of glacier termini, the images must be aligned digitally using image-analysis software on an image-analysis computer workstation. This "registration" of images is accomplished by locating features, "tie points," that are common to all images (for example, a large rock outcrop or a stable shoreline), and stretching each image to correspond to the master image. Approximately 60 tie points were used to register the images in this study.

Errors in Measurement of Glacier Changes

Satellite-derived measurements of change in glacier-terminus position can be accurate only to the resolution of the sensor used. In this study, we have used mostly MSS data, so changes in the position of glacier termini cannot have an accuracy better than 79 m. However, there are factors that may cause a further reduction in accuracy. Although every effort was made to perform an accurate



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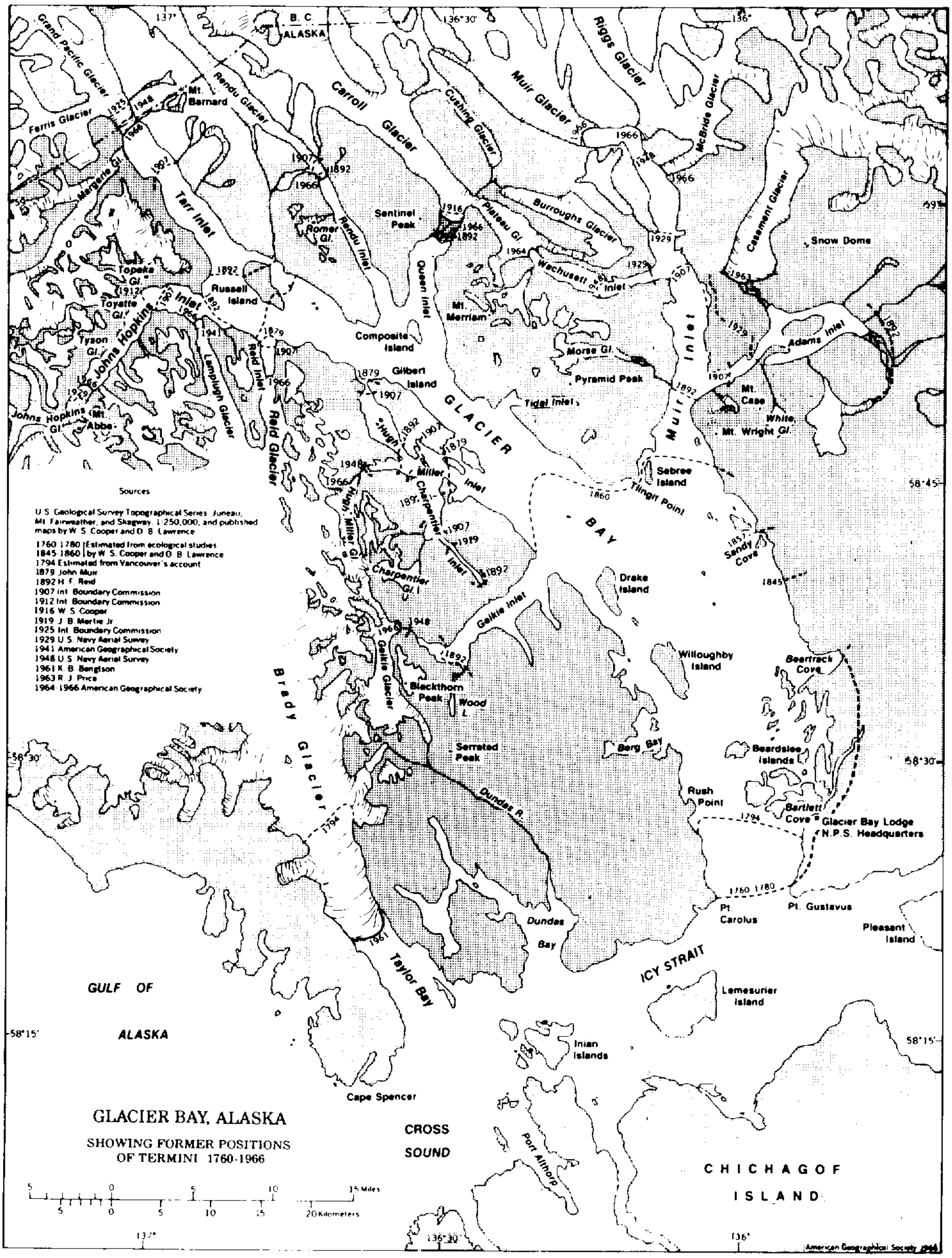

Fig. 4. Map showing changes in the terminus positions of glaciers in and near Glacier Bay (from Bohn, 1967).

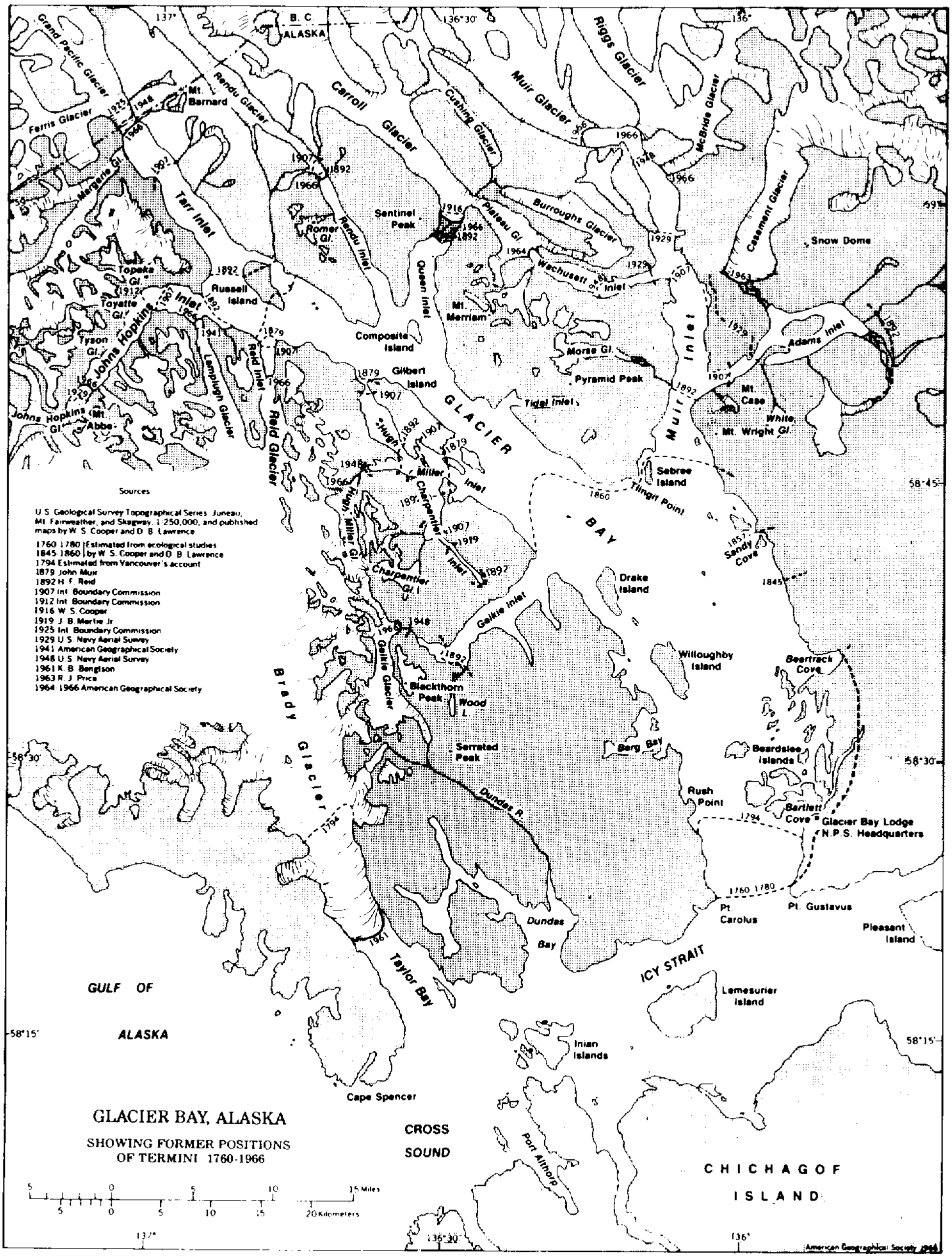

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Table 2. Approximate Changes in Glacier-Terminus Positions in and around Glacier Bay, Alaska[a]

Glacier	Change (km)	Rate (m/yr)
Brady	0.4 (1961–1992)	13
Burroughs	recession and shrinkage	(see text)
Carroll	5.1[b] (1966–1986)	255
Casement	–4.1[b] (1963–1986)	–178
Cushing	–1.5 (1966–1986)	– 75
Grand Pacific	0.8 (1966–1986)	40
Johns Hopkins	Stable	
Lamplugh	0.2 (1966–1986)	10
Margerie	0.5 (1966–1986)	25
McBride	–2.5 (1966–1986)	–125
Morse	Slight retreat	
Muir	–9.7[b] (1966–1986)	–485
Plateau	–5.9[b] (1964–1986)	–286
Reid	1.6[b] (1966–1986)	80
Rendu	–2.5[b] (1966–1986)	–125

[a]Minus (–) sign indicates recession; rate of change is also shown. Changes in glacier terminus position are not precise because of the inherent errors in using this technique (see text). Also, the rate of change is dependent upon where the measurement is taken on the glacier terminus.

[b]Terminus position was difficult to measure because debris on the glacier terminus had a spectral reflectance very similar to the surrounding sediment and iceberg-laden water.

registration of the Landsat scenes, the registration procedure introduces some error because there often are insufficient stable features available to be used as tie points.

Another source of error can occur when a glacier terminus (especially in the case of a stagnant or retreating glacier) is debris-covered, making it difficult to distinguish between the glacier terminus and the morainal material in the case of glaciers that terminate on land. In a study of the recession of the Pasterze Glacier, Austria, using both field and satellite measurements, Hall et al. (1992) determined the accuracy of the measurement of glacier terminus change to be approximately equal to the Landsat pixel resolution.

RESULTS AND DISCUSSION

Terminus-Position Change on Selected Glaciers

The time series of Landsat data also reveals the amount and rate of terminus-position change on the glaciers. The Muir Glacier retreated approximately 7.3 km between 1973 and 1992, with the rate of retreat being greater between 1973 and 1980. The average retreat, as measured using Landsat imagery, was 0.73 km/yr between 1973 and 1982, and only 0.04 km/yr between 1982 and 1992. This is consistent with reports indicating a slowing of the Muir's retreat by 1982 (Krimmel and Meier, 1989).

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[a]Minus (–) sign indicates recession; rate of change is also shown. Changes in glacier terminus position are not precise because of the inherent errors in using this technique (see text). Also, the rate of change is dependent upon where the measurement is taken on the glacier terminus.

[b]Terminus position was difficult to measure because debris on the glacier terminus had a spectral reflectance very similar to the surrounding sediment and iceberg-laden water.

registration of the Landsat scenes, the registration procedure introduces some error because there often are insufficient stable features available to be used as tie points.

Another source of error can occur when a glacier terminus (especially in the case of a stagnant or retreating glacier) is debris-covered, making it difficult to distinguish between the glacier terminus and the morainal material in the case of glaciers that terminate on land. In a study of the recession of the Pasterze Glacier, Austria, using both field and satellite measurements, Hall et al. (1992) determined the accuracy of the measurement of glacier terminus change to be approximately equal to the Landsat pixel resolution.

RESULTS AND DISCUSSION

Terminus-Position Change on Selected Glaciers

The time series of Landsat data also reveals the amount and rate of terminus-position change on the glaciers. The Muir Glacier retreated approximately 7.3 km between 1973 and 1992, with the rate of retreat being greater between 1973 and 1980. The average retreat, as measured using Landsat imagery, was 0.73 km/yr between 1973 and 1982, and only 0.04 km/yr between 1982 and 1992. This is consistent with reports indicating a slowing of the Muir's retreat by 1982 (Krimmel and Meier, 1989).

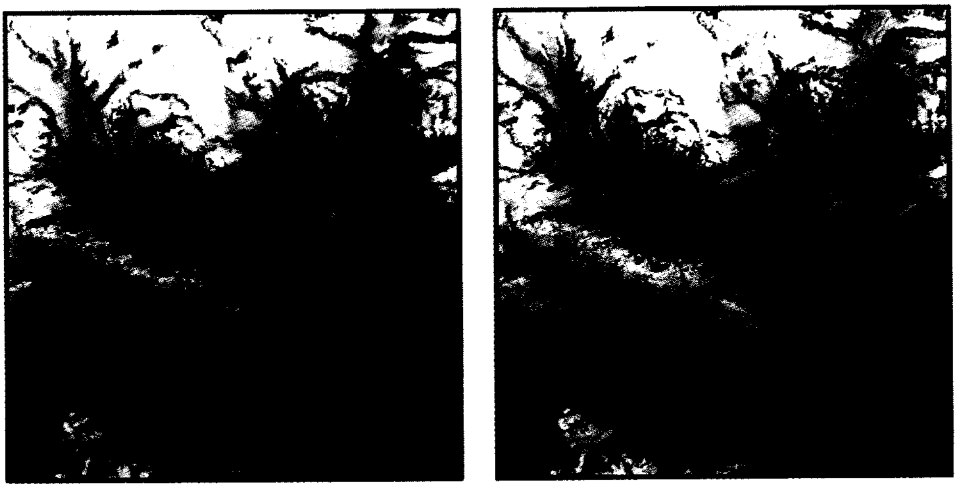


Fig. 5. Landsat MSS subscenes showing deglaciation of the area near Muir Inlet. The >7 km retreat of the Muir is shown and revegetation of the area is visible when comparing scenes. Arrows on the 1973 image (left) point to the Muir (left) and Burroughs (right) glaciers, respectively. Note that the amount of vegetation (shown in red) has increased from 1973 to 1986 (right image).

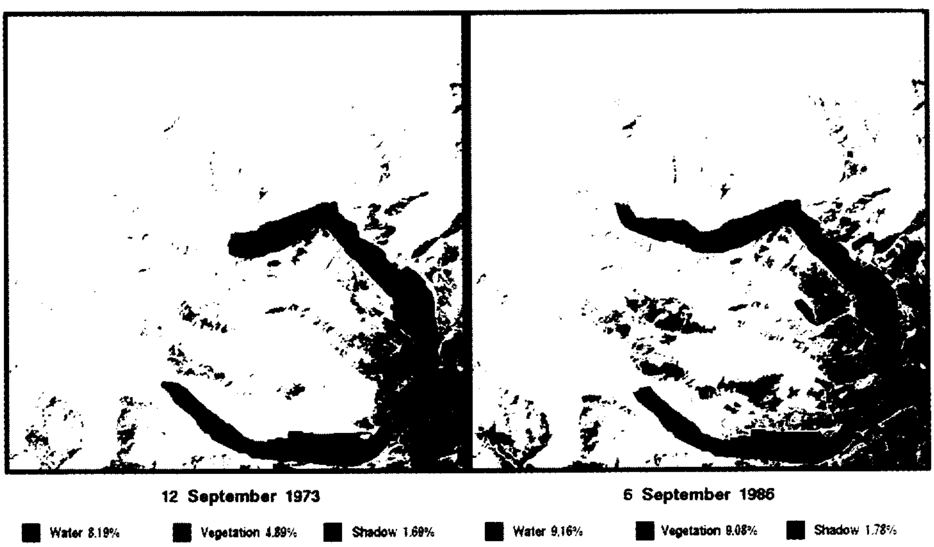
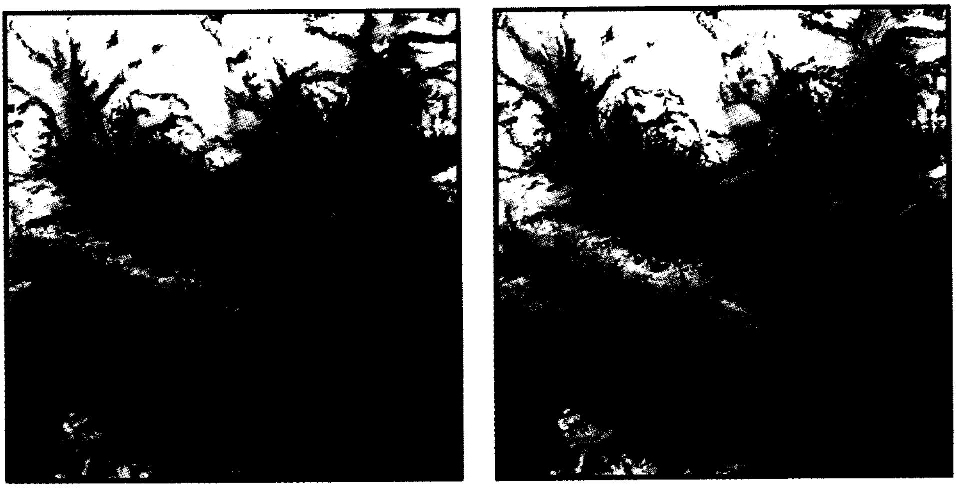


Fig. 6. Classified MSS subscenes (same as in Fig. 5) showing change in the areal coverage of ice (white), vegetation (red), and water (blue) and shadow (green), from 1973 to 1986.

Table 2 shows the net changes of some of the glaciers in Glacier Bay as determined between the 1960s and 1986. Note that while some termini have advanced, most have retreated or are stable.

The 1986 Landsat image (Fig. 5, right) shows the Burroughs Glacier cut off from nourishment. Formation of ice-margin lakes is evident when one compares the



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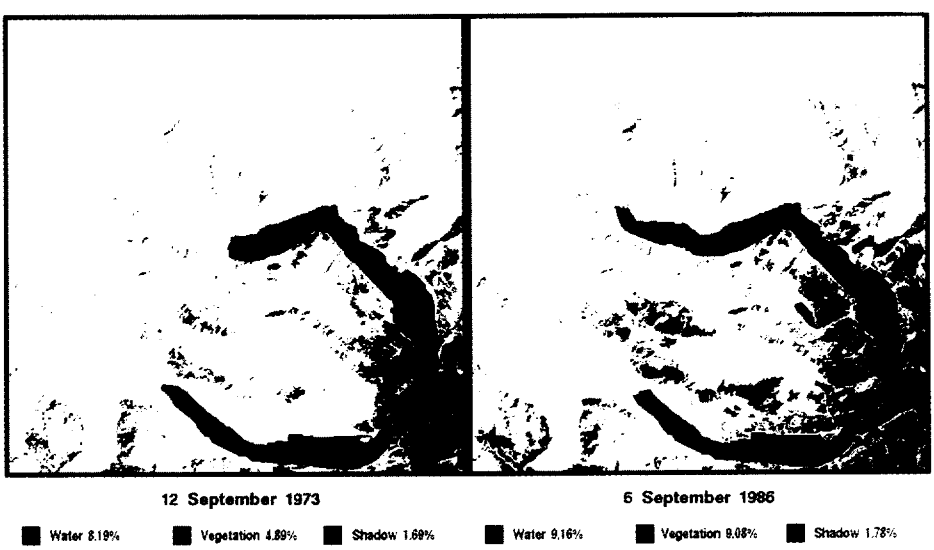

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Table 3. Percentage of Water and Vegetation in an MSS Subscene Containing the Muir Glacier

Date	Water	Vegetation	Glacier[a]
9/12/73	8.2	4.9	86.9
9/06/86	9.2	9.1	81.7

[a]Contains some miscellaneous pixels including snow in shadows.

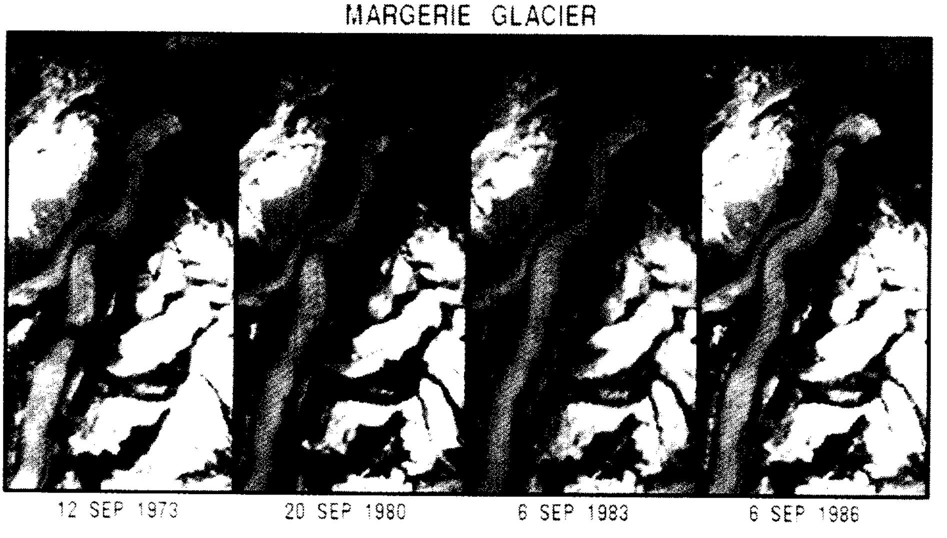

Fig. 7. Surface movement of ogives on the Margerie Glacier, as seen on Landsat imagery.

1973 and 1986 Landsat images in Figure 5; in particular, note the large lake that formed by 1986 just north of the Burroughs Glacier. Figure 6 shows classified subscenes of the area in Figure 5 and allows one to measure changes in the areas covered by ice, vegetation, and water, respectively (Table 3).

Effects of Deglaciation

A cursory look at the 12 September 1973 and the 6 September 1986 Landsat scenes reveals that the amount of vegetation increased dramatically between 1973 and 1986 (Fig. 5). This is the result of deglaciation and subsequent rapid regrowth of vegetation in areas previously covered by ice. The amount of glacier ice in the Landsat subscene (seen in Fig. 5) decreased by 87 km^2, or about 6%, from 1973 to 1986, while the amount of vegetation increased by 70 km^2, or about 86%, during the same period.

Surface Movement of the Margerie Glacier

Surface features can be observed to move downglacier on the Margerie Glacier, which flows into Tarr Inlet near the Grand Pacific Glacier. The Margerie is a rapidly

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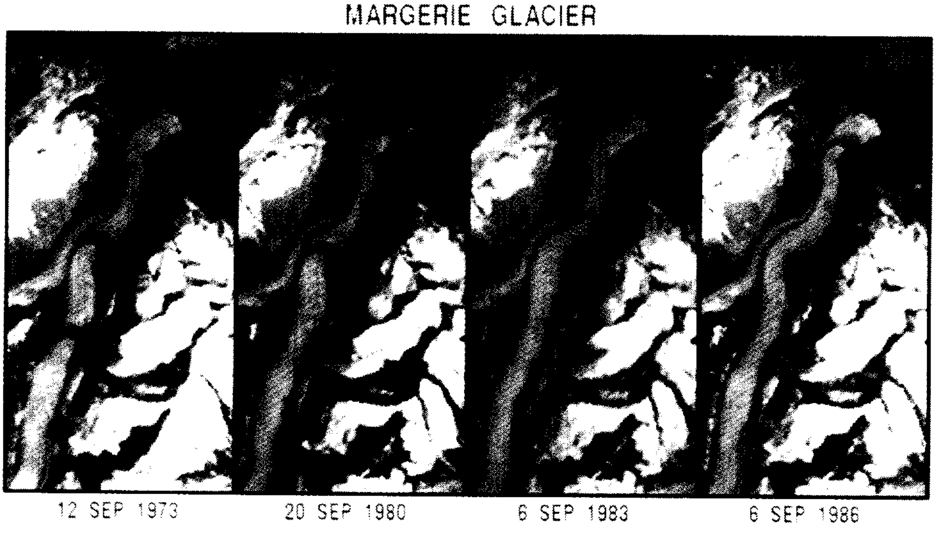

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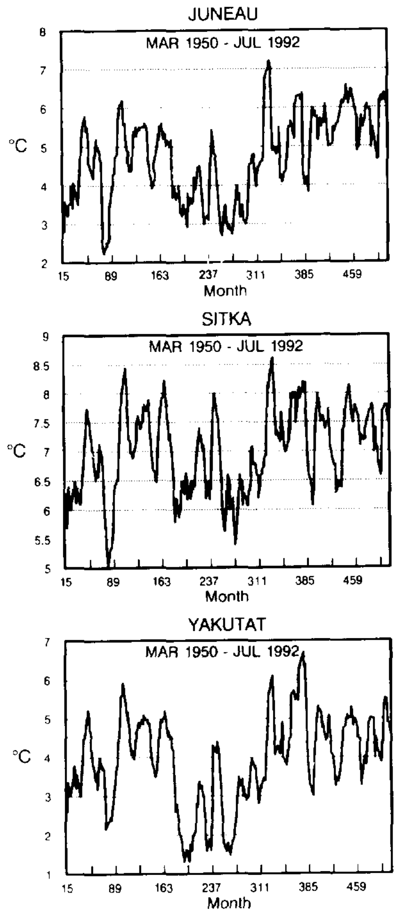

Fig. 8. Plots of one-year running means of average annual air temperature of three stations in southeastern Alaska. The month refers to calculation of the running mean and thus does not begin at month 1.

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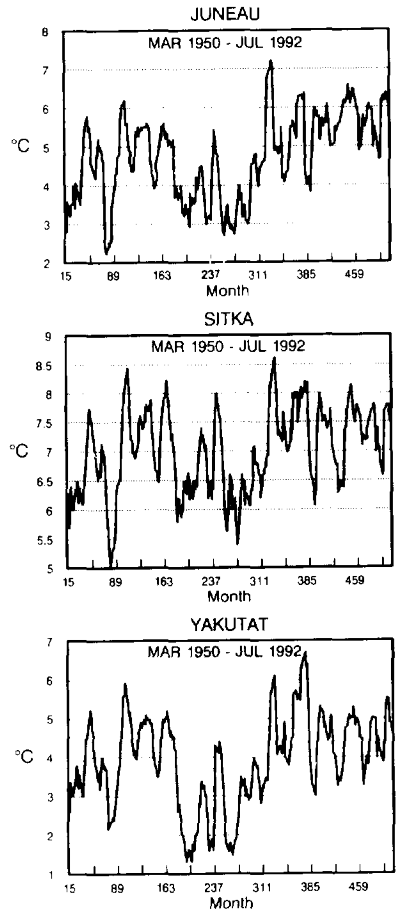
Climatological Data

Climatological data from the meteorological stations at Juneau, Sitka, and Yakutat have been studied (Figs. 8 and 9). In order to remove the annual trends, one-year running means were calculated. Results show a tendency, in at least the last two decades, toward higher average annual temperatures at all stations studied. In Figure 9, the five-year running mean data are plotted for the same



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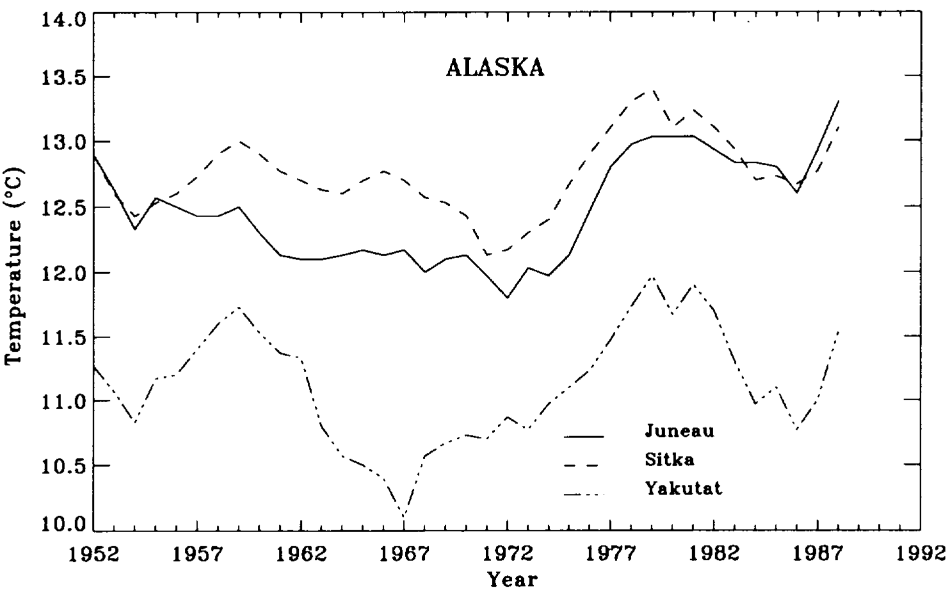


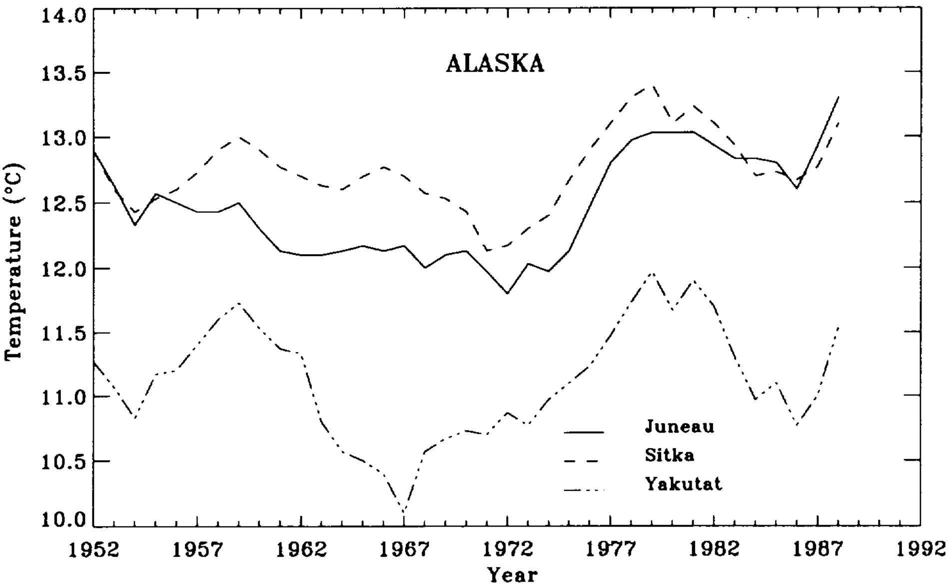
Fig. 9. Five-year running mean of average air temperatures for June, July, and August.

stations, but only for the months of June through August each year. This shows that the observed increase in summer temperatures is at least partly responsible for the higher average temperatures that have been observed at those stations over the last two decades.

CONCLUSION

In this paper, we have discussed the history of deglaciation of Glacier Bay and environs since the late 19th century. The combination of historical measurements (made by aerial reconnaissance and field measurements) and satellite data permits calculation of changes in the terminus position following deglaciation. Both the tidewater and non-tidewater glaciers of the area generally have been retreating, though some advances also have been noted. Mean annual air temperatures generally have increased during the period of record (from about the 1940s), with the greatest increases seen during the last 20 years. These increasing air temperatures likely are responsible for some of the recession of the non-tidewater glaciers.

It also may be observed that the process of deglaciation in these valleys tends to increase the rate of melting, because with less ice, the microclimate becomes warmer and the marginal and terminal barren zones, as they increase in size from ice recession, absorb more radiation than the ice-free or vegetation-covered areas. The process of deglaciation has positive feedback effects that cause progressively more rapid deglaciation without any necessity of the regional climate becoming warmer.



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